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**Involving local communities for effective citizen science:
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Involving local communities for effective citizen science: determining game species' reproductive status to assess hunting effects in tropical forests

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ABSTRACT

1. Involving communities in sustainable wildlife management in tropical forests can ensure food security and livelihoods of millions of forest dwellers that depend on wild meat, but also safeguard hunted species. Mathematical models have been developed to assess hunting sustainability; but these require empirical information on reproductive parameters of the prey species, often challenging to obtain.

2. Here, we suggest that if local people can accurately identify the reproductive status of hunted animals in the field, these data could fill the existing knowledge gap regarding species' life-history traits and enable better assessments of hunting impacts.

3. We first tested whether local people in 15 rural communities in three Amazonian sites could accurately diagnose, before and after training, the pregnancy status of hunted pacas (*Cuniculus paca*), which we use as our model. We then applied the results from these tests to correct reproductive status data of hunted specimens, voluntarily collected over 17 years (2002-2018) as part of a citizen science project in one of our study sites. We ran generalized additive models to contrast these corrected reproductive rates with those obtained from the direct analysis of genitalia by researchers, and with indices describing game extraction levels (catch-per-unit-effort, CPUE, and age structure of hunted individuals).

4. Before training, interviewees correctly diagnosed pregnancy in 72.5% of tests, but after training, interviewees accurately diagnosed pregnancy in 88.2% of tests, with high improvements especially for earlier pregnancy stages. Monthly pregnancy rates determined by hunters and by researchers were similar. Reported annual pregnancy

rates were negatively correlated with CPUE, and positively correlated with the percentage of immatures in the hunted population, in accordance to an expected density-dependent response to variations in hunting levels.

5. We showed that the voluntary diagnosis of game species' reproductive status by local people is a feasible method to obtain accurate life-history parameters for hunted tropical species, and to assess hunting effects on game populations. Given that almost half of the protected areas in the world are co-managed by local people, our results confirm the potential of integrating local communities in citizen science initiatives to ensure faster, low-cost, and more accurate data collection for wildlife management.

KEYWORDS: Bushmeat, citizen science, community-based monitoring, hunting, reproduction, tropical forests, Amazon, sustainability.

1 INTRODUCTION

Ensuring the sustainability of wildlife hunting in tropical forests is crucial to guarantee the conservation of game species and safeguard the food security and livelihoods of millions of forest dwellers (Coad et al. 2019). Since the early 1990s, a wide range of mathematical models have been developed to assess hunting sustainability (Weinbaum, Brashares, Golden, & Getz, 2013). These models require accurate information on population abundance, reproductive and mortality patterns of the hunted species (Weinbaum et al., 2013).

Reproductive performance of wild vertebrates is usually studied by directly examining animals after capture and restrain, or from direct field observations of births (e.g. Zhang et al., 2007). Because both methods are challenging, especially for tropical forest animals (Fragoso et al. 2016), researchers are limited by the lack of basic information on age of first reproduction, breeding cycles and pregnancy rates of hunted species (Milner-Gulland & Akçakaya, 2001). Moreover, such information is also essential for the development of complex demographic models, such as how reproductive rates change in response to the removal of individuals by hunting. These models are rarely applied due to the lack of data; thus, researchers employ simpler ones that perform with much higher uncertainty levels (Weinbaum et al., 2013).

A cost-effective option for gathering large amounts of biological and ecological evidence in the field is via citizen scientists (Dickinson, Zuckerberg, & Bonter, 2010). By involving non-professionals it is possible to obtain vital information on a variety of subjects (Bonney et al., 2014; Steger, Butt & Rooten, 2017). In the tropics, indigenous and rural people have been involved in citizen science projects, providing information on animal populations and trends, just as accurately as trained scientists (e.g. Danielsen et al., 2014). Since local communities in tropical forests have extensive knowledge of

the environment and are the main direct users of natural resources, their participation in scientific monitoring is central (Pocock et al. 2015).

Mayor, El Bizri, Bodmer, & Bowler (2017) have demonstrated the effectiveness of citizen science through a community-based collection of organs of Amazonian forest mammals to determine reproductive parameters. In this study, local hunters collected and voluntarily donated complete viscera of hunted specimens over an uninterrupted 15-year period. Using this material, Mayor et al. (2017) were able to estimate annual birth rates of female offspring. These estimates differed significantly from those obtained in sustainability assessments that often use data from captive populations.

As shown by Mayor et al. (2017) it is possible to collect accurate reproductive parameters of some hunted species over the long-term through the examination of biological materials brought back to researchers. This is possible for small-bodied animals but not for large species since their viscera are often not brought back from the forest due to their heavy weight (see Mayor et al., 2017). In the current system local people are only responsible for sample collection, since the determination of the reproductive status of animals is done by technicians in laboratories, thus increasing survey costs, and does not involve locals in data processing and analysis, and arguably in using the collected data in decision-making. Conversely, if local people could accurately categorise the reproductive status of hunted specimens where they are hunted, data collection becomes cheaper, easier to implement, and more frequent, therefore substantially increasing sample sizes. Beyond providing more precise estimates of reproductive rates, larger sample sizes would also permit the better understanding of hunting impacts, e.g. by determining how variation in reproductive rates over time relates to density-dependent responses of populations to hunting.

In this study, we used the lowland paca (*Cuniculus paca*) as our model species, because it is amongst the top three most hunted species in the Neotropics (e.g. Peres, 2000; El Bizri, Morcatty, Lima, & Valsecchi, 2015; El Bizri et al., 2019), allowing us to acquire a large number of samples. Using photographs of genitalia of paca females donated by hunter families, we tested whether an effective method could be implemented for citizen scientists to accurately diagnose the reproductive status of hunted specimens. We first established the local peoples' capacity to determine the reproductive status of female pacas in three Amazonian sites, before and after a period of training. We then used these results to correct the pregnancy rates estimated for the species from data collected by local people on hunted specimens' reproductive status over a 17-year period (2002-2018) in one study site. For this study site, we compared the corrected pregnancy rates with those determined from genitalia samples by trained researchers, and with hunting indices to describe the effects of hunting on the studied game populations.

2 MATERIALS AND METHODS

2.1 Study sites

We conducted our study in three Amazonian sites (Fig. 1). The Yavarí-Mirín River (YMR, 04°19'53" S; 71°57'33" W) is located in the Western Peruvian Amazon, and encompasses 107,000 ha of continuous upland forests where a single indigenous community of 307 inhabitants live (Fig. 1). The Amanã Sustainable Development Reserve (ASDR, 01°54'00" S; 64°22'00" W) is a 2,350,000 ha reserve of predominantly upland forests in the central Brazilian Amazon, between the Negro and Japurá Rivers. Approximately 4,000 riverine people inhabit 80 communities and some isolated settlements within this reserve. The middle Juruá River (MJR) region in southern

Brazilian Amazonia (MJR, 5°40'26"S, 67°30'25"W) comprises two protected areas of sustainable natural resources use (Middle Juruá Extractive Reserve and Uacari Sustainable Development Reserve) with 886,175 ha of lowland and upland forests. These two reserves are occupied by ca. 3,200 people in 57 settlements. In all three areas, local communities rely mainly on agriculture for income and on hunting and fishing for subsistence.

2.2 Local people interviews

Photographs were taken of all paca female genitalia collected (n=300) from animals donated for research by local people in the YMR and ASDR (see Mayor et al., 2013, 2017; El Bizri et al., 2018) (Appendix 1, Supporting Information). For pregnant genitalia, we removed the conceptuses and measured their crown-rump length using a metal Vernier calliper (maximum 300 mm).

From the pool of photographs, we selected a total of 42 showing complete genitalia, being 7 (16.7%) photographs of non-pregnant females and 35 (83.3%) from pregnant females with conceptuses ranging from 0.5 cm to 26 cm in length (mean = 7.51 cm; SD = 7.28 cm), depicting the increasing range in conceptus size along gestation. Using these photographs, we asked interviewees to answer whether they thought the specimen was pregnant or not. If they considered the specimen to be pregnant, the interviewee was requested to point out where he/she believed the conceptus was implanted within the uterus.

Considering the time available for the study, we used simple random sampling (Albuquerque et al., 2014) to select the maximum number of young and adults to interview within each sampled community. We interviewed a total of 104 people, 81 men (77.9%) and 23 (22.1%) women. The average age of the men was 38.7 ± 13.9 SD

(17-72) years old, and of women 41.3 ± 14.1 SD (24-75). Interviews were conducted in August 2017 in the single YMR community, in May and October 2018, and in January and June 2019 in five ASDR communities, and in November 2018 in nine communities in the MJR.

We held two rounds of interviews for each person during a single interview day. In the first round, we showed the pictures randomly and asked people to determine the reproductive status of each specimen without giving them any clues or guidance on the reproductive biology of the species. In the second round, we used three of the pictures to train interviewees on how pregnancy occurs, explaining where the conceptuses would normally be found in the uterus, and how to determine their presence. We then shuffled the photographs and randomly presented these again for their second diagnosis.

2.3 Hunting registers

In the ASDR, a citizen-science hunting monitoring system has been active since 2002 and is ongoing. In this site we trained five local hunters within five separate communities to assemble a wide range of data on the daily hunting activity of community members, including time spent hunting and number of hunters involved, as well as collect data on each specimen hunted: sex and the body mass of hunted individuals, and reproductive status of females (pregnant or non-pregnant). Hunters voluntarily provided information to collectors after returning from their hunts. By the end of 2018, collectors had recorded data for a total of 1236 hunted pacas.

All research was conducted in compliance with the research protocol approved by the Research Ethics Committee for Experimentation in Wildlife at the Dirección General de Flora y Fauna Silvestre from Peru (License 0350-2012-DGFFS-DGEFFS) and by the Instituto Chico Mendes for Biodiversity Conservation from Brazil (License

SISBIO No 29092-1).

2.4 Data analysis

Interview responses

For each interview, responses were scored as 1 if correct and 0 if incorrect. We considered an incorrect answer when the interviewee identified a non-pregnant paca as pregnant (false positive) and a pregnant paca as non-pregnant (false negative), also when the interviewee incorrectly indicated the location where the conceptus was implanted in the uterus.

We analysed all responses using generalized linear mixed models (GLMM) with a binomial distribution to obtain logistic regressions of the probability of interviewees giving correct answers according to a set of predictor variables. We generated separate models for non-pregnant and pregnant females. For non-pregnant specimens, we considered the number of correct and incorrect responses (scores: 0 – incorrect, 1 – correct) as the dependent variable, and the interviewees' sex (man/woman) and age (continuous) as predictor variables. For pregnant specimens, we considered the number of correct and incorrect responses (scores: 0 – incorrect, 1 – correct) as dependent variable, and the interviewees' sex and age and the length of the conceptuses (continuous) as predictor variables. We built a null model (no effect of predictor variables) and models with different combinations of predictor variables, from simple ones (only one predictor variable) to a more complex one (all variables in the model). We independently tested each interview round. Interviews from the same community may not be independent since there were: 1) a different number of interviewees for each community, and 2) because we consider that the learning process and sharing of information (of the biological traits of game species) among local people may be nested

at the community level. As a result of these two issues, the communities sampled were included as a random categorical factor.

Final models from GLMMs were compared based on Akaike Information Criterion (AIC) values, and all models with the $\Delta AIC < 2$ in relation to the model with lowest AIC were considered as with strong support (see Burnham & Anderson, 2004). To avoid selecting a model that was overfitting due to a large sample size, we also used a likelihood ratio test to compare the significance of these models; if two models were similar ($p > 0.05$), we considered the best-fitted model the one with lowest number of parameters, i.e. fewest degrees of freedom. However, we present all models with $\Delta AIC < 2$ in Appendix 2 (see Supporting Information). GLMMs were conducted using the R package *lme4*.

Finally, we assessed the effect of training on the probability of giving more correct answers in the second interview. For both non-pregnant and pregnant specimens, we calculated the difference between the percentages of correct and incorrect responses in the two interview rounds using a chi-square test. In addition, for pregnant specimens, we calculated the difference between the average logistic regression formulas produced in the GLMMs for each round.

Corrections of reproductive status and density-dependence effects

Interview results were then used to correct the data on the reproductive status of hunted females collected over the 17-year (2002–2018) monitoring period in the ASDR. Since no systematic training on pregnancy diagnosis was conducted with local people during the monitoring period, we considered they could be categorizing pregnant females as non-pregnant at a similar rate as obtained in the first interview round. On this basis, we therefore applied a correction factor based on two steps. First, we used the

formula of the relationship between conceptus length and gestational age in El Bizri et al. (2017) ($\text{Crown-rump length} = 0.179 * \text{Age} - 5.28$) to obtain the proximate number of pregnancy days up to which hunters would be mistakenly diagnosing pregnant pacas as non-pregnant. For this, we considered the threshold for an accurate diagnosis to be at a conceptus length in which the probability of giving a correct answer was 90%. Second, we used the monthly percentage of paca conceptions presented by El Bizri et al. (2018) as a proxy for the percentage of pacas that would be in the early days of pregnancy, not detectable as pregnant by the hunters. Based on the number of pregnancy days calculated from our first step, we calculated a retroactive monthly percentage of false negatives for each month, thus correcting the number of pregnant and non-pregnant females (see Appendix 3). The gestation length of 149 days for the paca was based on Guimarães et al. (2008).

We used these corrected reproductive data to validate the effectiveness of a long-term citizen science collection of reproductive performance data to: (1) provide reliable information on the reproductive rates for the species, and (2) understand hunting effects. For the first aim (1), we selected females with a body mass ≥ 5.5 kg, which we considered as mature, following El Bizri et al. (2019). We then calculated the monthly percentage of pregnant specimens among the mature females sampled each month (hereafter monthly pregnancy rate), independently for each year, and assessed the relationship between monthly pregnancy rate and the expected monthly pregnancy rate of pacas. For this purpose, we considered the published metrics of pregnancy rates in El Bizri et al. (2018), calculated from pregnancy diagnoses from genitalia collected in the ASDR by researchers and examined in the laboratory, as the expected monthly pregnancy rates (see Appendix 3). In this analysis, the month was treated as a fixed factor, while the year of collection was treated as a random factor.

For our second aim (2), we hypothesized that any hunting impact on any animal population would lead to an increase in pregnancy rates over time as a dense-dependent response to lower population abundance (e.g. Lima & Jaksic 1998). This increase in pregnancy rate would then be related to an increase in immature individuals in the population due to higher birth rates. We tested for all these relationships by calculating the yearly pregnancy rates of hunted specimens, correlating these with the mean annual catch-per-unit-effort (CPUE, $\text{in ind/hunter}^{-1}\text{hour}^{-1}$) of hunting events as a proxy of paca abundance (see Rist, Milner-Gulland, Cowlshaw, & Rowcliffe, 2009; Valsecchi et al., 2014; Marrocoli et al., 2019). Afterwards, we correlated the yearly pregnancy rates with the annual percentage of immature individuals (number of individuals < 5.5 kg/total number of individuals hunted) (see Mendes-Oliveira et al., 2012; El Bizri et al., 2018, 2019). Although 848 paca hunting events were recorded, we calculated CPUE for only nocturnal hunts using the ‘spotlighting’ method ($n=519$), since paca is strictly nocturnal and spotlighting is a technique that is specifically used to hunt this and no other species, therefore guaranteeing that this index indeed reflected the species’ abundance in the study area (see Valsecchi et al., 2014).

To assess the relationship between the monthly pregnancy rate and the expected monthly pregnancy rate of pacas, as well as dense-dependent effects, we used a generalized additive model (GAM), which consists of univariate regression analysis that allows each regression variable to have a linear or non-linear relationship with the dependent variable. The type of non-linearity is tested through the use of several smoothers/additive terms in the modelling process. These terms normally adds penalizations in the model to prevent overfitting. For the conduction of GAMs, we first tested the best family of distribution fitted to the response variable, comparing these based on QQ-plots of the residuals, and on the difference between AIC values among

them. After selecting the best-fitted distribution, we built a null model (no relationship with the predictor variable), and models with the predictor variables in linear and non-linear forms, testing penalized splines and cubic splines as additive terms. The final model, both in terms of retention of predictor variables and the type of relationship (whether linear or non-linear), was selected based on AIC values (Burnham & Anderson, 2004), in which the model with the lowest AIC was selected. For these analyses, the R package *gamlss* was used (Stasinopoulos & Rigby, 2007). An advantage of using the *gamlss* package is its flexibility in terms of families of distribution (over 100 continuous, discrete and mixed distributions for modelling the response variable are available), and the various additive terms available compared to other packages. We used R 3.3.3 software for all statistical procedures, and a p-value<0.05 was considered significant.

3 RESULTS

3.1 The diagnosis of the reproductive status by local people

For non-pregnant females, there was a proportion of 92.6% and 90.4% of correct responses in the first and second round of interviews, respectively, with no significant difference between rounds ($\chi^2=0.17$; $p=0.68$); no significant effect was observed for any of the predictor variables on the probability of giving correct responses (Table 1).

For pregnant females, the proportion of correct responses was 72.5% for the first interview round. The probability of correctly diagnosing pregnancy varied according to the conceptus size, the smaller the conceptus, the lower the probability (Table 1; Fig. 2a). This probability also varied according to the age of the interviewee, with younger answering correctly more often than older individuals; this difference being greater for small-sized conceptuses (Table 1; Fig. 2b). The average probability formula calculated

according to conceptus size was: Probability of Correct Responses = $1/1+e^{-(0.19*Foetal\ size-0.08)}$.

In the second round of interviews, after training, we recorded a total of 88.2% correct answers. The size of the conceptus still influenced the probability of giving correct answers (Table1; Fig. 2c-d). The average probability formula calculated according to conceptus size in the second round was: Probability of Correct Responses = $1/1+e^{-(0.57*Foetal\ size+0.45)}$, changing substantially from the first round of interviews due to significant improvements in the diagnosis of pregnancy after training ($\chi^2=236.65$; $p<0.0001$). This improvement occurred for all conceptus sizes, but was higher for pregnant females with smaller conceptuses, between 0.5 and 10 cm (32-85 gestation days, 21.5-57.0% of total gestation length, respectively), with peak at around 5 cm (57 gestation days, 38.3% of total gestation length), for which diagnoses improved by around 25% (Fig. 3).

3.2 Estimates of reproductive rates of game species and hunting effects

Out of the total number of hunted individuals recorded in our monitoring programme (n=1236 pacas), 634 were females out of which 554 were mature (87.6%, ≥ 5.5 kg). Among these, local dwellers classified 445 as non-pregnant and 109 as pregnant. Without any correction, the average monthly pregnancy rate from hunting registers was 22.7% (Table 2). Using the formula obtained from the first round of interviews, we estimated that hunters would start diagnosing pregnancies with $\geq 90\%$ accuracy for conceptuses larger than 12.6 cm in length. This length corresponds to around 100 days gestational age (El Bizri et al., 2017). Thus, by including a retroactive 3-month time-lag (~ 90 days) to the percentage of conceptions provided by El Bizri et al. (2018), the average monthly pregnancy rate increased by 19.3%, reaching 42.0%

with the inclusion of 108 females that were in fact pregnant but incorrectly diagnosed as non-pregnant (Table 2).

Corrected monthly pregnancy rates were positively and significantly correlated with the expected monthly pregnancy rates calculated from genitalia collections (El Bizri et al., 2018) (Table 1; Fig. 4). The annual pregnancy rates calculated from hunting registers were on average 39.1%, presenting an inverted U-shaped pattern of changes across years, with a peak in 2012 (Table 3; Fig. 5). Pregnancy rates were negatively correlated with the annual CPUE over time (Table 1; Fig. 6a), and years with higher pregnancy rates had a higher proportion of immature individuals (Table 1; Fig. 6b).

DISCUSSION

We showed that local people can participate in the voluntary diagnosis of the reproductive status of game species. Although we used the lowland paca as our model species, this method can be used for any hunted tropical forest placental mammal because: i) these share similar internal reproductive morphology; ii) worldwide, local people eviscerate specimens before eating their meat; and iii) pregnancy is a phenomenon that can be easily identified by hunters.

The high score obtained in the first round of interviews shows that most interviewees already possessed ample understanding of the reproductive biology of game species. This traditional ecological knowledge (TEK) probably starts from exposure to animals since childhood (da Cunha, 2009). At a very young age, children of both sexes are initiated into hunting practices via storytelling, and during puberty, young teens follow adults to hunts and assist in the butchering and cooking of animals (Bonwitt et al., 2017; MacDonald, 2007). This TEK on the reproductive cycles of species play a particularly important role in influencing the younger generation's

capacity to detect and hunt animals, and can be used in local management strategies to avoid overhunting (Berkes, Colding, & Folke, 2000). Vieira, von Muhlen, and Shepard (2015), in a study in the Brazilian Amazon, indicated that hunters communally agreed not to take pregnant females or hunt during the reproductive season to guarantee the sustainability of game populations. In another example, hunters' impressions of the body condition of adult female barren-ground caribou (*Rangifer tarandus*) in Canada corresponded to the reproductive status of the animals after dissection (see Lyver & Gunn 2004). Thus, if pregnant animals can be identified during hunting events, it may be possible to develop more effective management strategies that take into account the reproductive biology of the game species.

Several interviewees were unable to identify small conceptuses in pictures of pregnant genitalia. Though we acknowledge that a number of interviewees may have guessed their answers, we argue that they may have classified them as non-pregnant actually believing they were correct, given the difficulty in detecting early pregnancies. This is supported by the rate of correct responses for non-pregnant specimens, which was much higher than expected in a random guessing situation (90% vs. 50%, respectively).

In our study, before the training, younger people were better at diagnosing pregnancy than older people. This could be explained by two factors: hunting frequency decreases with age, and therefore younger people may be more frequently in contact with hunted animals; and older people claimed that their weaker vision impaired them for properly seeing small conceptuses in the pictures, so younger people may have benefited from the method used in the study. Conversely, as exemplified in other citizen scientist studies (e.g. Ratnieks et al., 2016), we showed that after a short training session

the difference between these age groups was overcome and we significantly improved our interviewees' ability at diagnosing pregnancy, especially for early pregnancy stages.

Thus, we claim that local peoples' ability at diagnosing pregnancy after training is similar overall, and will be even higher when they are handling the specimens themselves, since they would be able to palpate the uterus in search for any sign of pregnancy, as they do while processing game. A previous training also allows for a direct calculation of pregnancy rates without the need for extensively correcting the data as we did here, considering that only a small proportion of pregnant individuals (around 10% from very early gestations) would be incorrectly diagnosed, which is similar to the proportion of under-detected pregnancies by transabdominal ultrasonography (Mayor et al., 2005). Our claim is supported by the strong match between local and laboratory diagnoses of pregnancy, which shows that citizen scientists in rural communities are able to collect accurate information of the natural cycle of the species in the wild.

Our citizen-science monitoring of annual reproductive rates has also proved to be reliable for assessing density-dependent responses of populations to hunting, which is difficult to obtain in the field. To our knowledge, this technique has not been applied for tropical game species before our study. In addition, the lowest pregnancy rate value obtained in our study (64.5%) is similar to that obtained by Mayor et al. (2017) through genitalia collections in the Peruvian Amazon (62.8%), used to refine the intrinsic rate of population increase (r_{max}) in the paca. Mayor et al. (2017) estimated a minimal cost of \$2.75 per biological sample obtained through community-based collections. Therefore, in the present study, the citizen-science diagnosis of pregnancy generated savings of US\$1,743.50 for the paca alone. Accordingly, we advocate that the method presented here can be useful for faster, easier, low-cost, and accurate assessments of sustainability. Using this method to properly assess hunting impacts would aid more effective

strategies to protect wildlife from overexploitation, and decision makers and local leaders can be provided with accurate tools to implement tangible policies aimed at minimizing food insecurity.

Globally, around 45% of the protected areas are fully or co-managed by local people (UNEP-WCMC & IUCN 2016; Garnett et al., 2018), and thus, subjected to direct human use of fauna. We believe that the present method shows great potential to be applied in several contexts around the world, and even improved when integrated into new technologies currently used in participatory monitoring systems, such as smartphones and specific monitoring software (see van Vliet et al., 2017).

Very few studies on life history parameters of tropical species have relied on data obtained in the wild, and even fewer have obtained such data with the collaboration of local people, even though these are the main actors responsible to manage game populations. Here, we provide a tool to overcome the challenge of obtaining reproductive data on game species in the wild, offering a practicable method that improves sample size for wildlife research. We confirmed that the diagnosis of pregnancy in game specimens undertaken by local people integrated in a citizen science program is useful to assess hunting effects and provides accurate data for evaluating hunting sustainability for tropical mammals. Finally, this study offers the opportunity for locally-produced-data to be integrated into educational programs and policies, providing significant information that can be used against food insecurity and wildlife overexploitation worldwide.

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AUTHOR CONTRIBUTIONS

This work is part of HREB doctoral studies, supervised by JEF and PM. HREB and PM conceived the project and designed the methodology. HREB, LPL, JVCS, CFAVN, JV and PM collected the data. HREB, JEF and PM analysed the data. HREB, JEF, LPL and PM led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data are available via the PANGAEA Data Publisher at <https://doi.pangaea.de/10.1594/PANGAEA.906209>

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TABLES

Table 1. Details of the best-fit generalized linear mixed models (GLMMs) for the diagnoses of mature paca (*Cuniculus paca*) females by local people through genitalia pictures, and generalized additive models (GAMs) for the relationship between the corrected monthly pregnancy rate from hunting registers with the expected pregnancy rate from genitalia, the trend in annual pregnancy rates along the hunting monitoring period (2002-2018), and between annual pregnancy rates with the catch-per-unit-effort (CPUE, ind/hunter⁻¹hour⁻¹) and proportion of immature individuals in the Amanã Sustainable Development Reserve (ASDR). The interviewees' communities were included as a random categorical factor in the GLMMs.

Best-fit model					Family of Distribution ^a	Link function	wAIC (k; df; ΔAIC null) ^b
Response variables	Predictor variables	Estimate (SE)	z-value/t-value	P-value			
Interview - Pregnant pictures							
<i>First round</i>							
Correct answers	(Intercept)	0.433 (0.20)	2.21	0.0272	BI	Logit	0.71 (4; 4; 576.19)
	Conceptus size	0.190 (0.01)	18.01	<0.001*			
	Interviewee age	-0.001 (0.003)	-2.98	0.0029*			
<i>Second round</i>							
Correct answers	(Intercept)	0.452 (0.16)	2.85	0.0044*	BI	Logit	0.25 (3; 3; 457.06)
	Conceptus size	0.569 (0.05)	11.64	<0.001*			
Interview - Non-pregnant pictures							
<i>First round</i>							
Correct answers	(Intercept)	2.640 (0.30)	8.90	<0.001*	BI	Logit	0.35 (3; 3; 2.53)
	Interviewee sex	1.788 (1.04)	1.72	0.086			
<i>Second round</i>							
Correct answers	(Intercept)	2.687 (0.37)	7.28	<0.001*	BI	Logit	0.50 (3; 3; 2.17)
	Interviewee sex	15.774 (17.42)	0.01	0.993			
Monthly pregnancy rate							
From hunting registers	(Intercept)	-9.910 (4.83)	-2.05	0.042	BCCGo	Identity	0.65 (14; 15.5; 31.80)
	From genitalia	1.042 (0.15)	6.79	<0.001*			
Temporal trends							
Annual pregnancy rate	(Intercept)	-0.002 (0.16)	-146.00	<0.001*	IG	Identity	0.99 (3; 4.9; 15.86)
	<i>pb</i> (Year)	1.169 (0.008)	148.10	<0.001*			
Density-dependent responses							
Annual pregnancy rate	(Intercept)	67.83 (11.56)	5.87	<0.001*	GA	Identity	0.86 (2; 3; 3.58)
	CPUE	-118.95 (44.37)	-2.68	0.018*			
Proportion of immatures	(Intercept)	8.00 (4.11)	1.95	0.072	GU	Identity	0.87 (2; 3; 3.79)
	Annual pregnancy rate	0.26 (0.10)	2.65	0.019*			

Note: * $p < 0.05$. Smoothers were fitted using p-splines (pb). IG=Inverse Gaussian; BI = Binomial, BCCGo = Box Cox Cole Green Original, GU = Gumbel. SE = Standard Error. $wAIC$ = Akaike weights; k = number of parameters; df = degrees of freedom; ΔAIC null = difference between the AIC of the selected model and the AIC of the null model.

Table 2. Details on the number of mature paca (*Cuniculus paca*) females hunted in the Amanã Sustainable Development Reserve per month with their reproductive status, and the monthly pregnancy rates obtained from hunting registers before and after a correction. For more details on the calculations, see Appendix 3.

Month	Number of mature females			False negatives ^a	Monthly pregnancy rate (%) ^b	Corrected monthly pregnancy rate (%) ^c	Expected monthly pregnancy rate (%) ^d
	Pregnant	Non-pregnant	Total				
January	6	19	25	5.3	24.00	45.33	35.82
February	10	27	37	7.1	27.03	46.23	40.11
March	16	31	47	9.2	34.04	53.71	48.71
April	10	26	36	7.8	27.78	49.32	47.28
May	6	35	41	11.7	14.63	43.09	51.58
June	12	43	55	13.6	21.82	46.51	53.01
July	15	103	118	27.1	12.71	35.68	50.14
August	10	74	84	14.3	11.90	28.91	42.98
September	8	45	53	3.9	15.09	22.54	32.95
October	8	26	34	4.1	23.53	35.60	34.38
November	7	7	14	1.5	50.00	60.53	35.82
December	1	9	10	2.7	10.00	36.84	31.52
Total/Average	109	445	554	108.3	22.7	42.02	42.02

Note: ^aEstimated number of females that were incorrectly diagnosed as non-pregnant when they were in fact pregnant (false negatives). ^bPregnancy rate calculated from interviews with local people before correction. ^cPregnancy rate calculated from interviews corrected based on the number of false negatives. ^dExpected monthly pregnancy rates based on calculations using data from genitalia collections obtained in El Bizri et al. (2018).

Table 3. Details on the number of mature paca (*Cuniculus paca*) females hunted in the Amanã Sustainable Development Reserve per year with their reproductive status, the annual pregnancy rates obtained from hunting registers after a correction, the catch-per-unit-effort (ind/hunter¹hour⁻¹) (CPUE) of nocturnal paca hunting events and the proportion of immatures (individuals < 5.5 kg) within the total number of individuals hunted. For more details on the calculations, see Appendix 3.

Year	Number of mature females			Pregnancy rate (%)	CPUE (ind/hunter ¹ hour ⁻¹)	Proportion of immatures (%)
	Pregnant	Non-pregnant	Total			
2002	1	37	38	21.93	0.31	17.57
2003	1	31	32	22.43	0.27	12.05
2004	3	25	28	30.01	0.33	15.63
2005	5	22	27	37.82	0.31	12.24
2006	7	41	48	33.88	0.25	12.77
2007	8	32	40	39.30	0.21	3.37
2008	3	35	38	27.19	0.24	10.38
2009	6	18	24	44.30	0.21	8.57
2010	12	23	35	53.59	0.16	19.40
2011	7	19	26	46.22	0.27	10.00
2012	19	23	42	64.54	0.21	28.41
2013	9	30	39	42.38	0.22	12.66
2014	6	22	28	40.73	0.24	18.67
2015	5	15	20	44.30	0.18	25.81
2016	11	38	49	41.75	0.21	10.23
2017	3	9	12	44.30	0.28	22.73
2018	3	25	28	30.01	0.21	21.21
Total/Average	109	445	554	39.10	0.24	15.39

FIGURE CAPTIONS

Figure 1. A map showing the three sampled sites with locations of the 15 communities within Amazonia where interviews on the reproductive status of game species were performed (interview sites), between 2017 and 2019, and of the 5 communities where hunting and reproductive data was provided by local people in a citizen-science project between 2002 and 2018 (monitoring sites). Note that three communities in the Amanã Sustainable Development Reserve participated in both interviews and monitoring collections, and thus are classified as “monitoring and interviews sites”.

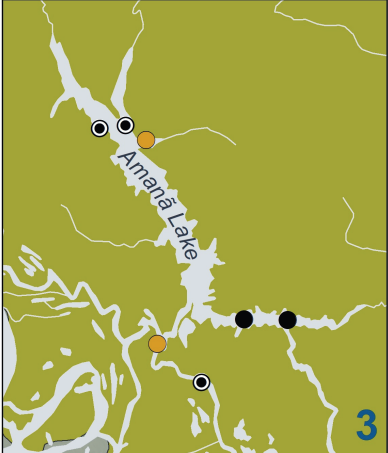
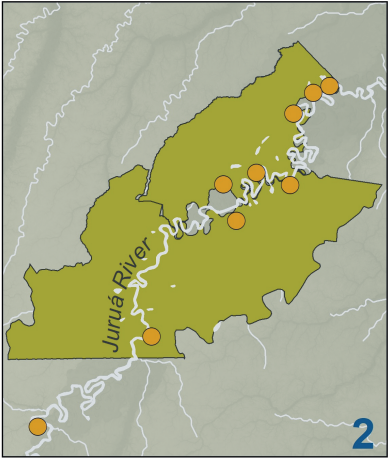
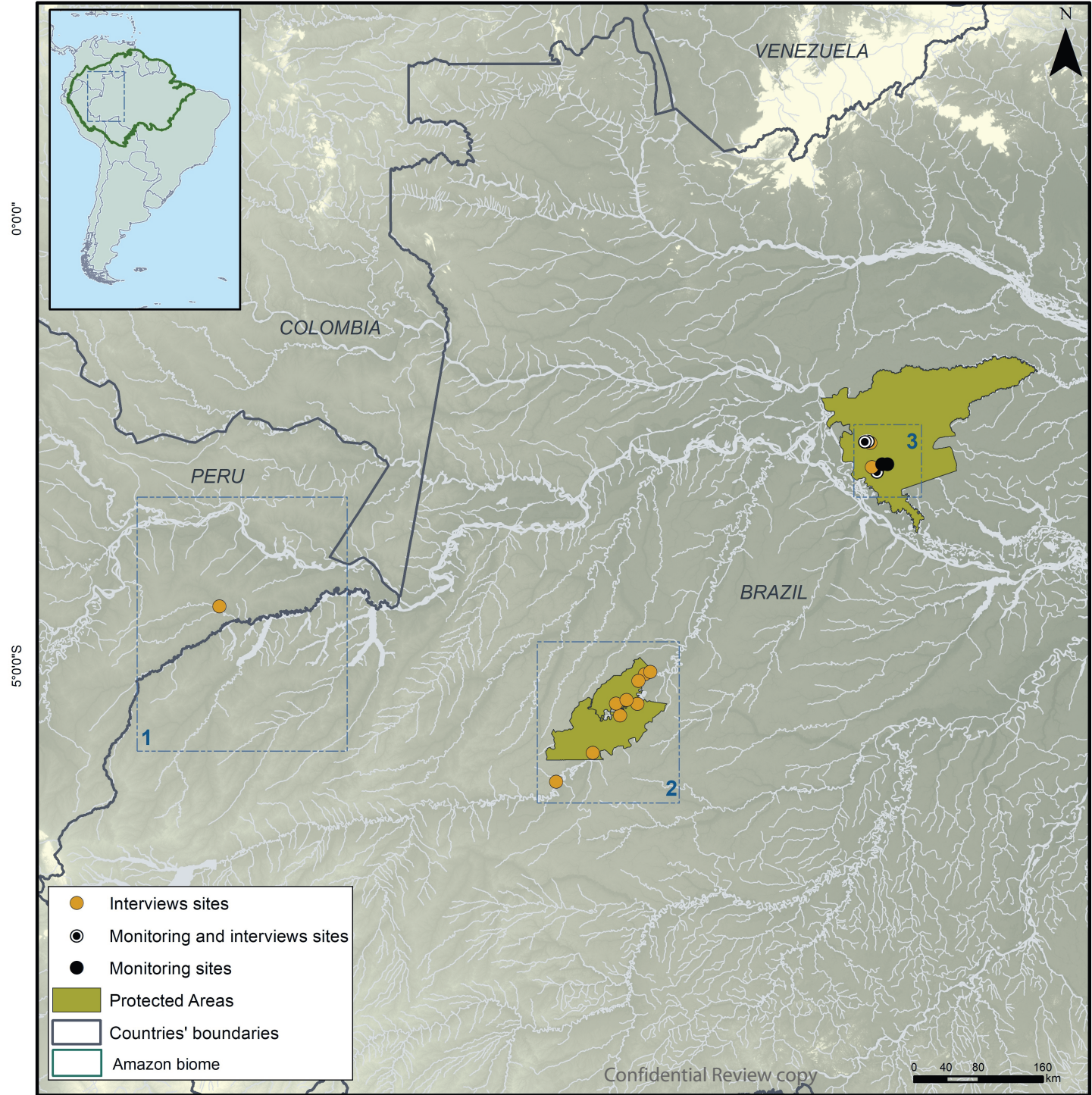
Figure 2. Probability of local people at correctly diagnosing pregnancy in pictures of genitalia of lowland pacas (*Cuniculus paca*) before (*a* and *b*) and after training (*c* and *d*), according to sex and age of the interviewee along the increase in conceptus size in pregnancy. Each line of graphs *a* and *c* represents one of the 104 people interviewed in this study.

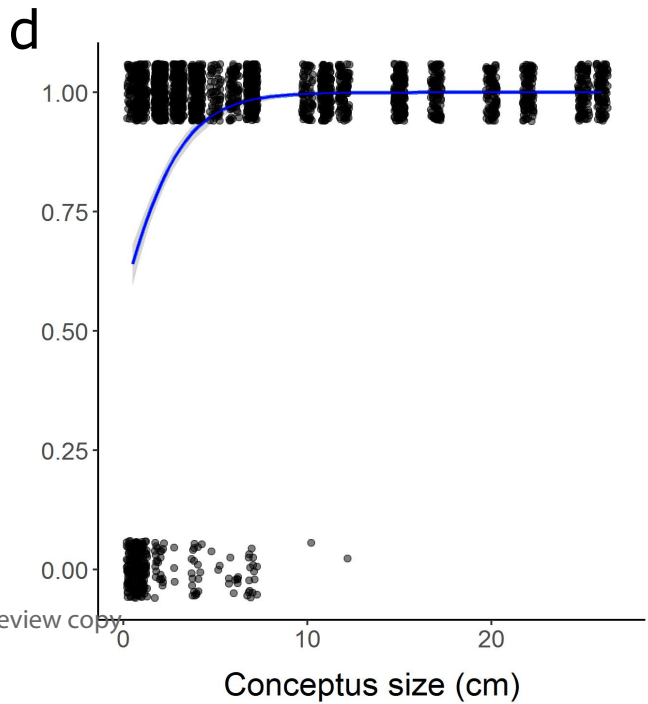
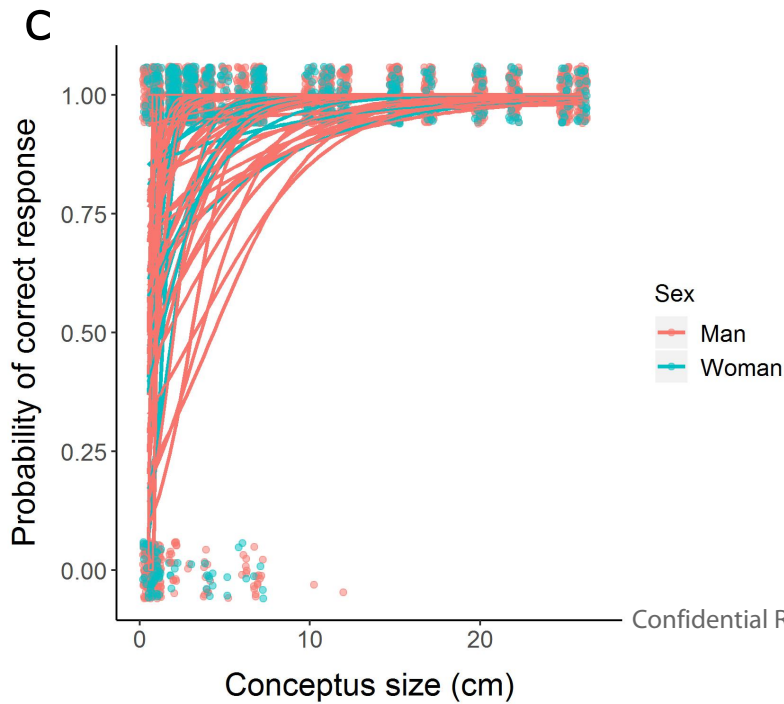
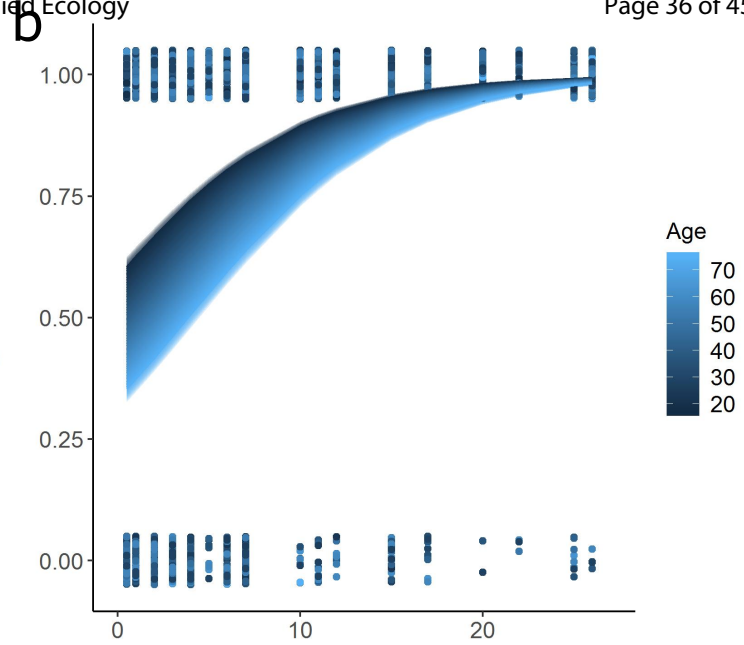
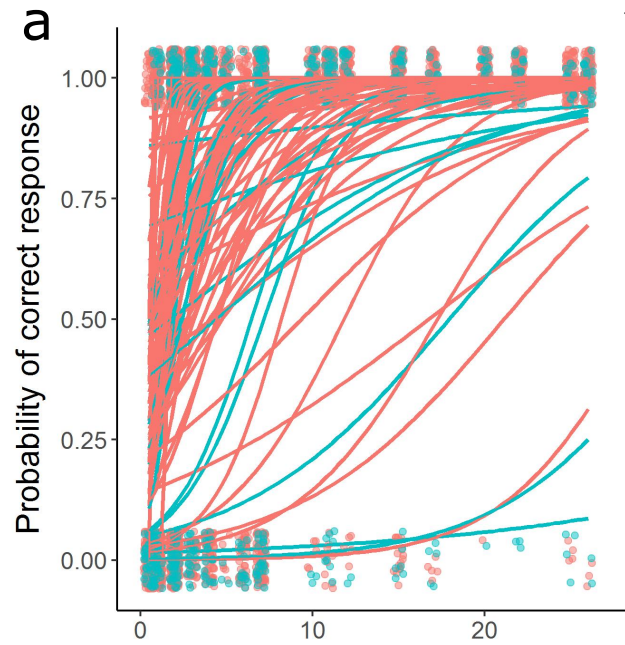
Figure 3. Improvement rate, in percentage, of the probability of local people in Amazonia at correctly diagnosing pregnancy in pictures of genitalia of lowland pacas (*Cuniculus paca*) after a training session.

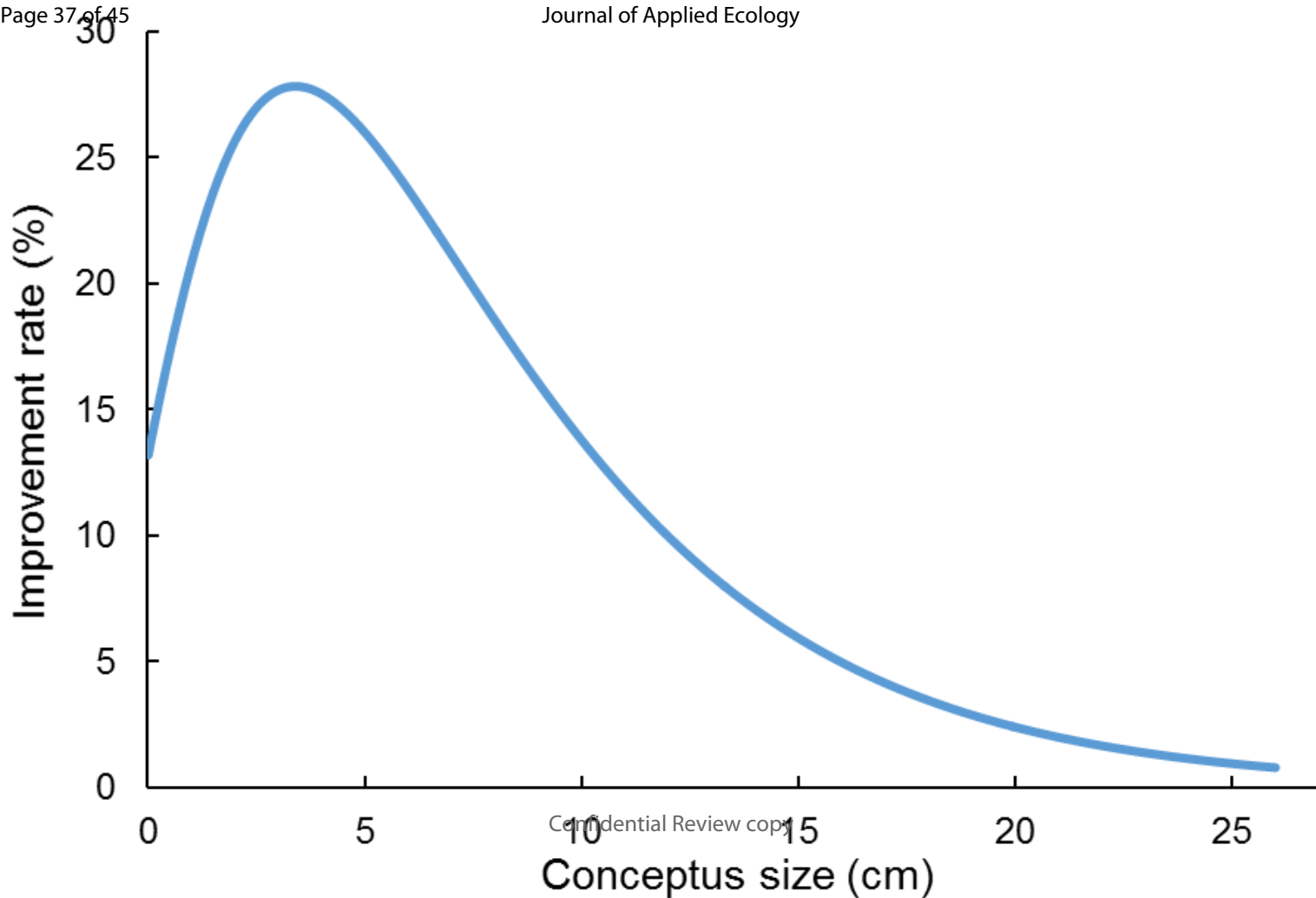
Figure 4. Relationship between the monthly pregnancy rates of lowland pacas (*Cuniculus paca*) determined by researchers through genitalia examinations and by hunting registers conducted by local people along 17 years in the Amanã Sustainable Development Reserve. Data on the pregnancy rates from genitalia were obtained from El Bizri et al. (2018).

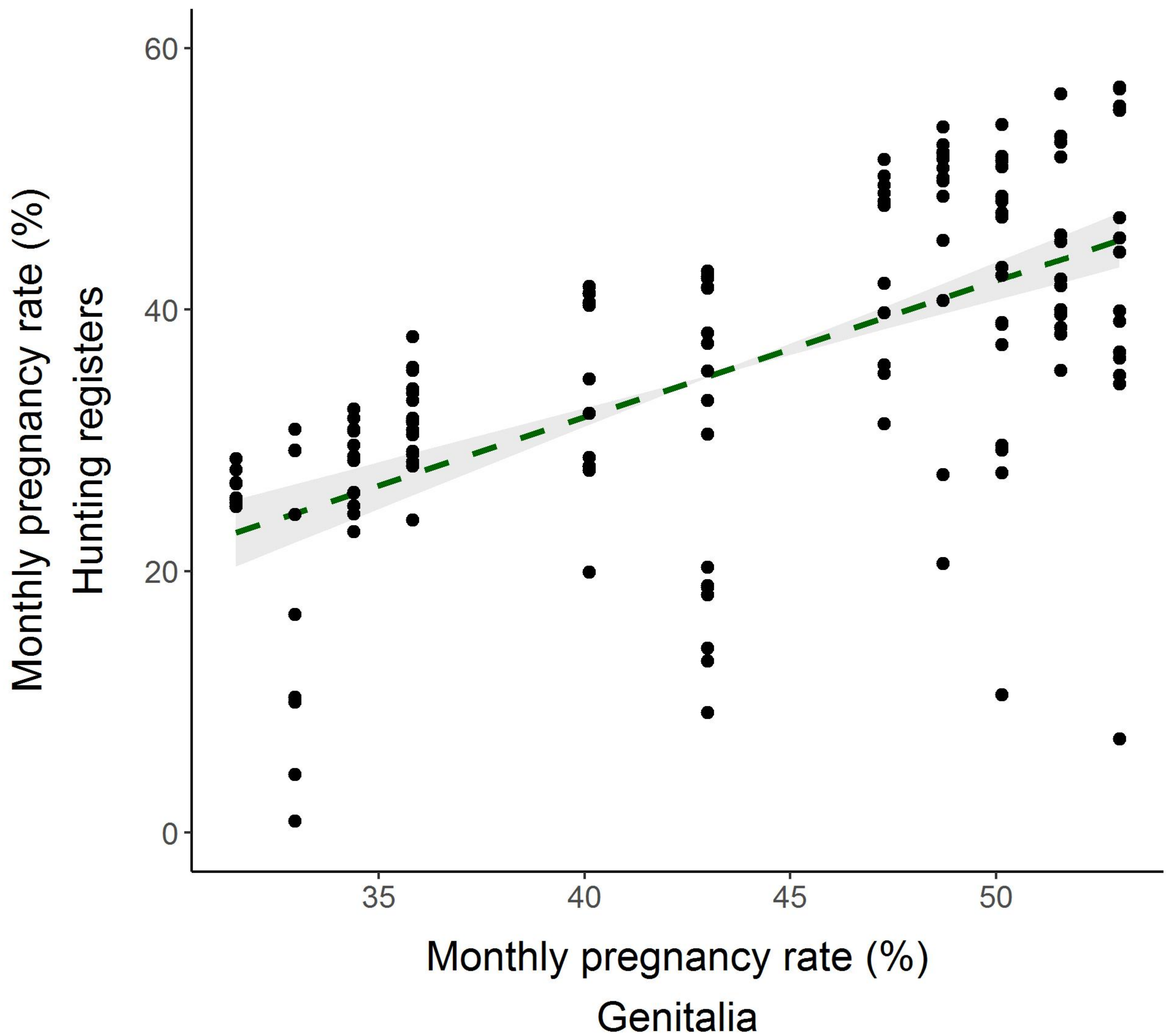
Figure 5. Temporal trends of annual pregnancy rates of lowland pacas (*Cuniculus paca*) determined by hunting registers conducted by local people along 17 years in the Amanã Sustainable Development Reserve.

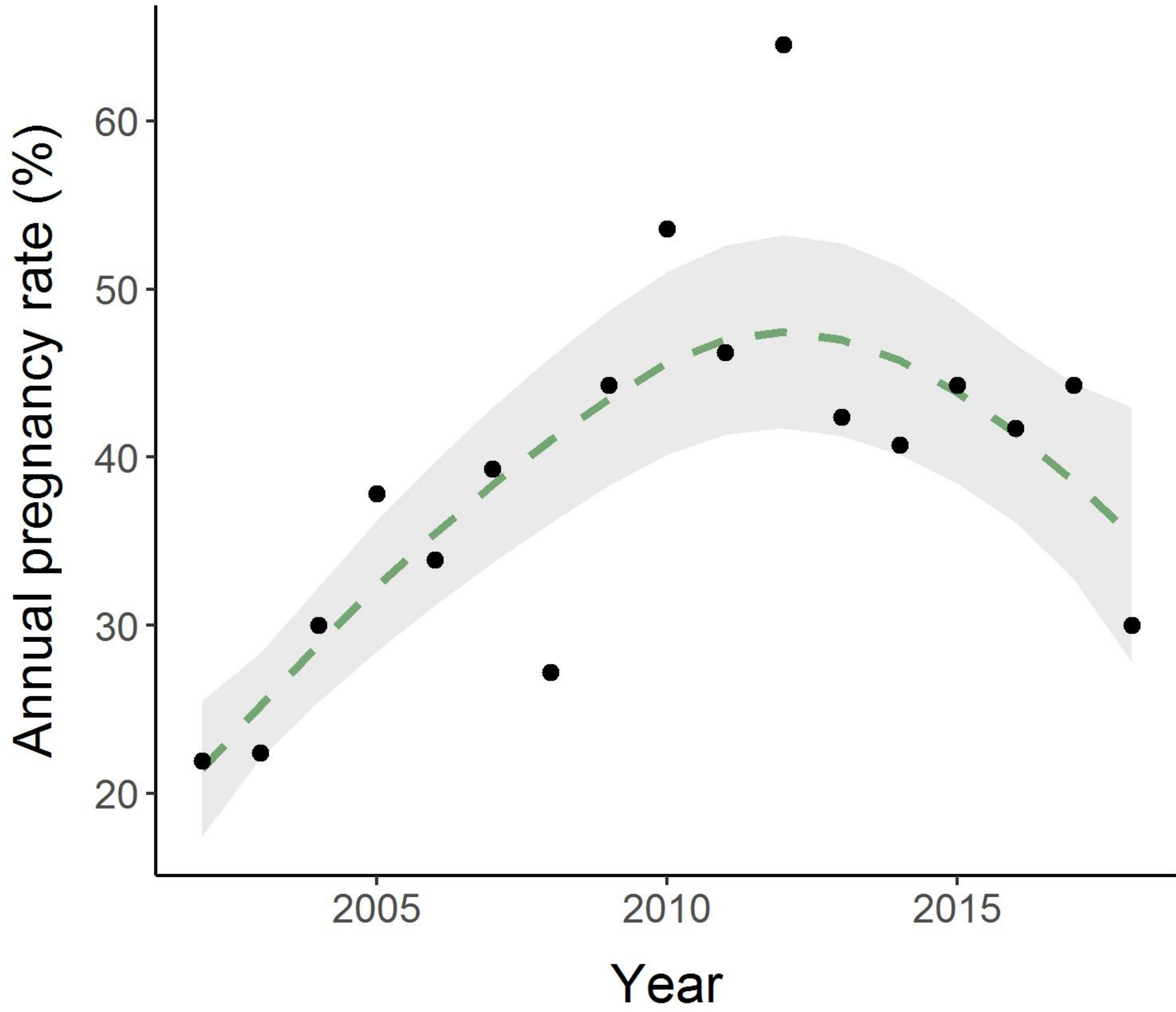
Figure 6. Relationship between the catch-per-unit-effort (CPUE) and annual proportion of immature individuals in hunted populations with the annual pregnancy rates of lowland pacas (*Cuniculus paca*) determined by hunting registers conducted by local people along 17 years (2002-2018) in the Amanã Sustainable Development Reserve.

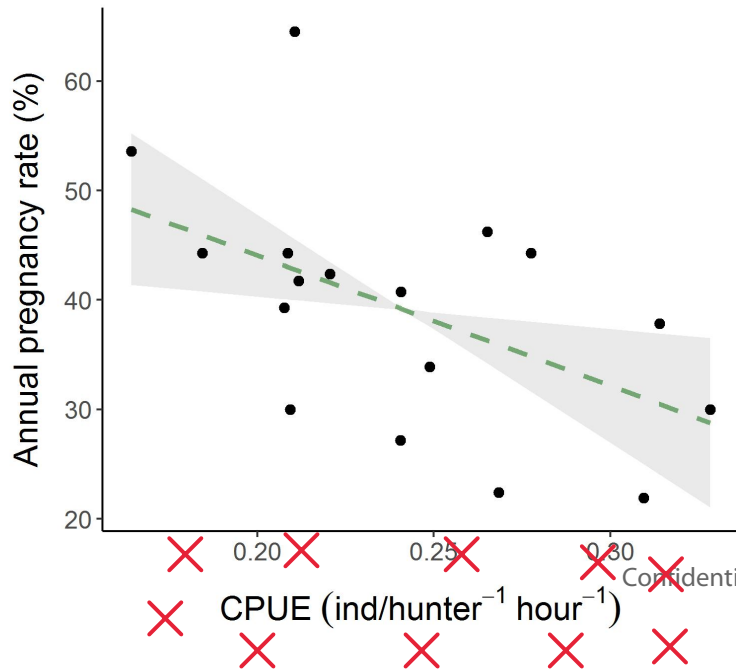
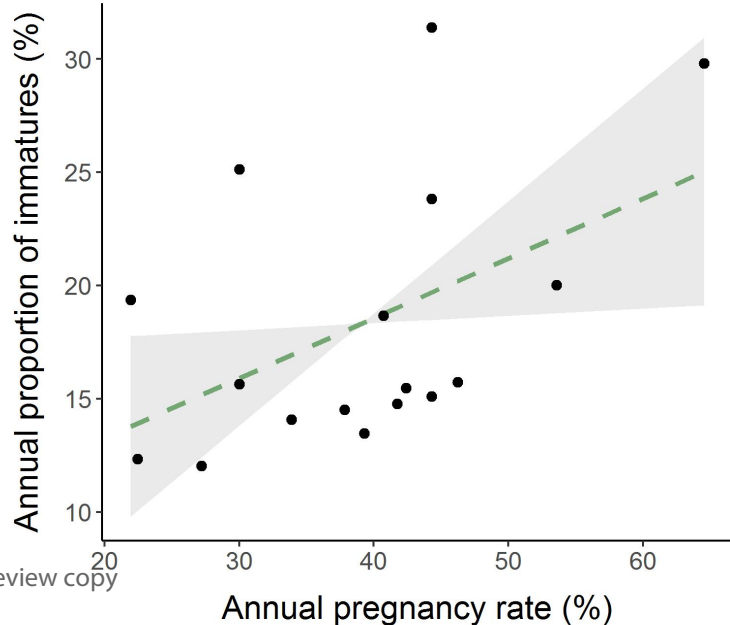










a**b**



Appendix 1. Pictures of *Cuniculus paca* genitalia used in interviews for the diagnosis of pregnancy status by local people. “a” and “b” consist of non-pregnant genitalia, while “c” and “d” consist of pregnant genitalia, with a 3-cm- and a 11-cm-conceptus, respectively.

Appendix 2. Alternative Generalized Linear Mixed Models for the diagnosis of reproductive status of lowland paca (*Cuniculus paca*) by local people in which the difference with the best-fitted model using a likelihood ratio test was non-significant.

Best-fit model					Family	Link	wAIC	Likelihood
Response variables	Predictor variables	Estimate (SE)	z-value	P-value	of Distribution	function	(k; df; ΔAIC)	ratio test (χ^2 ; df; P-value)
Interview - Pregnant pictures								
<i>First round</i>								
Correct answers	(Intercept)	0.4372 (0.20)	2.217	0.0266*	BI	Logit	0.27 (5; 5; 1.97)	0.0273; 1; 0.87
	Conceptus size	0.1899 (0.01)	18.012	<0.001*				
	Interviewee age	-0.0100 (0.003)	-2.976	0.0029*				
	Interviewee sex	-0.0188 (0.11)	-0.165	0.8688				
<i>Second round – model 1</i>								
Correct answers	(Intercept)	0.3998 (0.17)	2.362	0.0182*	BI	Logit	0.36 (4; 4; 0.75)	2.7539; 1; 0.10
	Conceptus size	0.5678 (0.05)	11.629	<0.001*				
	Interviewee sex	0.2898 (0.18)	1.644	0.1002				
<i>Second round – model 2</i>								
Correct answers	(Intercept)	0.6086 (0.26)	2.317	0.0205*	BI	Logit	0.23 (5; 5; 0.18)	3.8231; 2; 0.15
	Conceptus size	0.5690 (0.05)	11.632	<0.001*				
	Interviewee age	-0.0055 (0.005)	-1.037	0.2998				
	Interviewee sex	0.2848 (0.17)	1.616	0.1062				
Interview - Non-pregnant pictures								
<i>First round</i>								
Correct answers	(Intercept)	3.2405 (0.56)	5.814	<0.001*	BI	Logit	0.29 (4; 4; 0.38)	1.6228; 1; 0.20
	Interviewee sex	1.8144 (1.05)	1.726	0.0843				
	Interviewee age	-0.0156 (0.01)	-1.300	0.1935				
<i>Sencond round</i>								
Correct answers	(Intercept)	2.8350	3.850	<0.001*	BI	Logit	0.19 (4; 4; 1.94)	0.0554; 1; 0.81
	Interviewee sex	0.1563	0.010	0.9923				
	Interviewee age	-0.0038	-0.235	0.8145				

Note: *p<0.05. BI = Binomial. SE = Standard Error. wAIC = Akaike weights; k = number of parameters; df = degrees of freedom; ΔAIC null = difference between the AIC of the selected model and the AIC of the null model.

Appendix 3. Calculations of corrected pregnancy rates of lowland paca (*Cuniculus paca*) females from hunting registers, and expected pregnancy rates through genitalia examinations.

Number of adult females hunted according to their reproductive status in the Amazon													
Month	Non-pregnant	Pregnant	Total	Pregnancy rate (%)									
January	19	6	25	24.00									
February	27	10	37	27.03									
March	31	16	47	34.04									
April	26	10	36	27.78									
May	35	6	41	14.63									
June	43	12	55	21.82									
July	103	15	118	12.71									
August	74	10	84	11.90									
September	45	8	53	15.09									
October	26	8	34	23.53									
November	7	7	14	50.00									
December	9	1	10	10.00									
Total	445	109	554	22.7									
Concepcion rate (%)	Correction of the number of pregnant females using the monthly rate of conception with a 2-month time-lag ^a												
	Month	January	February	March	April	May	June	July	August	September	October	November	December
8.8	January	8.8	8.8	8.8	-	-	-	-	-	-	-	-	-
7.0	February	-	7.0	7.0	7.0	-	-	-	-	-	-	-	-
14.0	March	-	-	14.0	14.0	14.0	-	-	-	-	-	-	-
8.8	April	-	-	-	8.8	8.8	8.8	-	-	-	-	-	-
10.5	May	-	-	-	-	10.5	10.5	10.5	-	-	-	-	-
12.3	June	-	-	-	-	-	12.3	12.3	12.3	-	-	-	-
3.5	July	-	-	-	-	-	-	3.5	3.5	3.5	-	-	-
3.5	August	-	-	-	-	-	-	-	3.5	3.5	3.5	-	-
1.8	September	-	-	-	-	-	-	-	-	1.8	1.8	1.8	-
10.5	October	-	-	-	-	-	-	-	-	-	10.5	10.5	10.5
8.8	November	8.8	-	-	-	-	-	-	-	-	-	8.8	8.8
10.5	December	10.5	10.5	-	-	-	-	-	-	-	-	-	10.5

Results									
Month	Non-pregnant	Pregnant	Total	Pregnancy rate	False negatives	Corrected pregnancy rate	Monthly percentage of pregnant females ^b	Expected pregnancy rate ^b	Difference
January	19	6	25	24.00	5.3	45.33	7.10	35.82	9.5
February	27	10	37	27.03	7.1	46.23	7.95	40.11	6.1
March	31	16	47	34.04	9.2	53.71	9.66	48.71	5.0
April	26	10	36	27.78	7.8	49.32	9.38	47.28	2.0
May	35	6	41	14.63	11.7	43.09	10.23	51.58	-8.5
June	43	12	55	21.82	13.6	46.51	10.51	53.01	-6.5
July	103	15	118	12.71	27.1	35.68	9.94	50.14	-14.5
August	74	10	84	11.90	14.3	28.91	8.52	42.98	-14.1
September	45	8	53	15.09	3.9	22.54	6.53	32.95	-10.4
October	26	8	34	23.53	4.1	35.60	6.82	34.38	1.2
November	7	7	14	50.00	1.5	60.53	7.10	35.82	24.7
December	9	1	10	10.00	2.7	36.84	6.25	31.52	5.3
Total	445	109	554	22.7	108.3	42.02	100	42.02	0.0

^a The time-lag was calculated using the formula obtained from the first round of interview, through which we estimated that local people would start correctly diagnosing pregnancies (with 90% probability) for fetuses above 12.6 cm of length, corresponding to around 100 days of age (~ 3 months) (El Bizri et al. 2017). Monthly percentage of conceptions were obtained from El Bizri et al. (2018).

^b These values were obtained from El Bizri et al. (2018), who calculated pregnancy rates from a collection of uterus of lowland pacas in the Amazon. The expected pregnancy rate was calculated based on the expected monthly representativeness of pregnant females among all adult females.

Model species

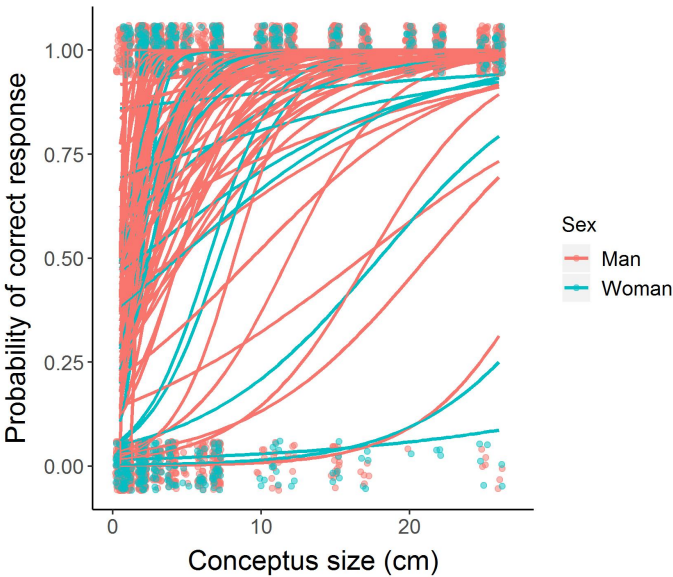


Cuniculus paca



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Before training



After training

